Economic comparison of common treatment protocols and J5 vaccination for clinical mastitis in dairy herds using optimized culling decisions

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ABSTRACT

This study used an existing dynamic optimization model to compare costs of common treatment protocols and J5 vaccination for clinical mastitis in US dairy herds. Clinical mastitis is an infection of the mammary gland causing major economic losses in dairy herds due to reduced milk production, reduced conception, and increased risk of mortality and culling for infected cows. Treatment protocols were developed to reflect common practices in dairy herds. These included targeted therapy following pathogen identification, and therapy without pathogen identification using a broad-spectrum antimicrobial or treating with the cheapest treatment option. The cost-benefit of J5 vaccination was also estimated. Effects of treatment were accounted for as changes in treatment costs, milk loss due to mastitis, milk discarded due to treatment, and mortality. Following ineffective treatments, secondary decisions included extending the current treatment, alternative treatment, discontinuing treatment, and pathogen identification followed by recommended treatment. Average net returns for treatment protocols and vaccination were generated using an existing dynamic programming model. This model incorporates cow and pathogen characteristics to optimize management decisions to treat, inseminate, or cull cows. Of the treatment protocols where 100% of cows received recommended treatment, pathogen-specific identification followed by recommended therapy yielded the highest average net returns per cow per year. Out of all treatment scenarios, the highest net

returns were achieved with selecting the cheapest treatment option and discontinuing treatment, or alternate treatment with a similar spectrum therapy; however, this may not account for the full consequences of giving nonrecommended therapies to cows with clinical mastitis. Vaccination increased average net returns in all scenarios.

Key words: dairy cow, clinical mastitis, economic, dynamic programming

INTRODUCTION

Clinical mastitis (CM) causes major losses in dairy herds due to reduced milk production (Hortet and Seegers, 1998; Rajala-Schultz et al., 1999; Gröhn et al., 2004), reduced conception (Loeffler et al., 1999; Hertl et al., 2010, 2011), and increased risk of mortality and culling for infected cows (Gröhn et al., 1998; Seegers et al., 2003; Heikkilä et al., 2012). Low profit margins in the dairy industry put pressure on farms to manage mastitis as economically as possible, and many studies have used dynamic programming to estimate the cost of CM and value of pathogen-specific information in its management (Houben et al., 1994; Bar et al., 2008; Cha et al., 2011, 2014).

The model used in these studies generates economically optimal management decisions to keep (and treat), inseminate (and treat), or cull cows with CM incorporating (a) individual cow characteristics such as parity, milk yield, conception rate, CM history, and disease status, and (b) the type of pathogen causing CM, its effect on milk yield, mortality, conception rates, and probability of a second or third case of CM. Decisions to keep, inseminate, or cull cows are optimized by the model. Keeping or inseminating a cow with CM implicitly means that the cow is treated. The form this treatment takes is defined by the treatment protocol, which describes what is done on farm as a first treatment. In our study, we used a dynamic programming model to

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estimate and compare the costs of common treatment protocols for CM.

Many different pathogens cause CM; treatment effectiveness is influenced by the pathogen causing CM, drug choice, and treatment duration (Owens et al., 1997; Sol et al., 2000; Gillespie et al., 2002). Antimicrobial treatment may not be of therapeutic benefit for all pathogens causing mastitis (Guterbock et al., 1993; Roberson, 2012); however, is widely used on farm to treat CM (Erskine et al., 2003; Sawant et al., 2005; Pol and Ruegg, 2007). Heavy penalties associated with antibiotic residues in milk, the limited drugs approved for use in lactating animals in the United States, and the potential risk of developing antimicrobial resistance further emphasizes the need for prudent drug use in CM cases (Morley et al., 2005; Neeser et al., 2006; Roberson, 2012). Use and choice of drugs for CM (i.e., treatment protocols for CM) varies between farms (Sawant et al., 2005; Pol and Ruegg, 2007; Hill et al., 2009).

The gold standard approach to treating CM is to take a milk sample from the infected quarter of a cow and send it for culturing on site or at an external laboratory (Neeser et al., 2006; Roberson, 2012). The culture result of a case of CM is identified within 24 to 48 h. If indicated by the culture results, an effective, targeted treatment can then be provided to the affected cow. This reduces the use of inappropriate or unnecessary antibiotics, minimizing treatment costs and discarded milk, but entails a delay in waiting for results, and the cost of sending samples for culture.

Many farms choose treatments without pathogen-specific information (Roberson, 2012). Common treatment approaches without pathogen identification involve treatment using a broad-spectrum antimicrobial (Hill et al., 2009), the product with the shortest milk/slaughter withhold or the cheapest treatment option. Cows can be treated straight away without the cost of culturing; however, the chosen treatment may be unnecessary or ineffective against the pathogen causing CM. Common actions following unsuccessful treatments include extending the current treatment, changing to an alternate treatment, or discontinuing treatment.

Overtreatment of CM with ineffective drugs leads to increased drug use, increased treatment costs, increased milk discarded due to treatment, and increased risk for meat and milk residues (Neeser et al., 2006; Lago et al., 2011; Roberson, 2012).

J5 vaccination is a commonly used preventative measure against CM caused by coliform bacteria such as *Escherichia coli* and *Klebsiella*. Coliform bacteria are often implicated in severe cases of CM. Benefits of vaccination include reduced milk loss due to mastitis (Wilson et al., 2008, 2009) and reduced mortality and

culling (Wilson et al., 2007). The role of vaccination in reducing the incidence of mastitis is inconclusive, with different studies finding it to reduce incidence by 80% (Gonzalez et al., 1989), 70% (Cullor, 1991), or not at all (Wilson et al., 2007).

Treatment protocols for CM can be highly individualized, and few studies have economically compared realistic treatment protocols for CM (Van Eenennaam et al., 1995; Shim et al., 2004). The strategies outlined above broadly encompass common treatment protocols for CM. The objective of this study was to estimate and compare the cost of common treatment protocols and vaccination, to identify an economically optimal treatment protocol. Our study aimed to identify if it is economical to culture a milk sample and provide targeted treatment to cows, or to treat cows using other common strategies for managing CM without pathogen identification. This can help farmers to make decisions about how they should treat their cows for CM, while accounting for factors that influence cow value, CM risk, and treatment costs.

MATERIALS AND METHODS

Economic Model

The economic model used to simulate the effects of different treatment protocols has been used previously to model the cost of CM in dairy cows (Cha et al., 2014). Built using the multilevel hierarchic Markov process (Kristensen, 2003) as the application program, the model is constructed as a 3-level hierarchic Markov process.

The first level contains state variables of permanent traits throughout the cow's lifespan, divided into months representing an entire lactation (level 2). This is further divided into individual months during the lactation (level 3). Level 1 contains 5 permanent milk yield categories; -5 , -2.5 , 0 , $+2.5$, and $+5$ (kg) from the mean daily milk production level, representing a cow's genetic potential to produce milk. In level 2, 5 possible whole-lactations are modeled, including a carryover state from lactation 2 onward that identifies whether cows had a case of CM in the preceding lactation (yes/no). In level 3, 20 mo of lactation are modeled, with the first month divided into the first 3 d following calving, and the rest of the month. At each month, a cow is described by one level of the following states: temporary (daily) milk yield (5 levels), pregnancy status (9 levels; 0 = open, $1-7$ = $1-7$ mo pregnant and milking, 8 = last 2 mo of pregnancy and dry), 1 involuntary culled state, and 9 CM states.

The 9 CM states included (0) no CM, (1) *Staphylococcus* spp., (2) *Staphylococcus aureus*, (3) *Streptococcus*

spp., including *Streptococcus uberis* and *Streptococcus dysgalactiae*, (4) *Escherichia coli*, (5) *Klebsiella*, (6) other treated (this included *Enterobacter*, *Enterococcus*, *Citrobacter*, *Serratia*, *Pasteurella*, *Corynebacterium* species, *Pseudomonas*, *Proteus*, *Corynebacterium bovis*, gram-positive bacillus, gram-negative bacillus, fungus, *Streptococcus* group C, mold, and *Nocardia*), (7) other not treated (this consists of pathogens unlikely to respond to antimicrobial treatment that would not be treated if identified, and includes *Trueperella pyogenes*, *Mycoplasma*, *Prototheca*, and yeast), and (8) negative culture: contamination and no significant organisms (>2 bacterial species on the culture plate). “No significant organisms” is defined as a culture plate containing more than 2 different species with no bacterial growth of either *Staph. aureus* or *Strep. agalactiae*, where the cases exhibited signs of CM. For each pathogen group, a history variable, H, indicates whether the cow had not previously had CM in that lactation (H = 0), or if it is the first, second, or third or more case of CM since calving (H = 1, 2, and 3, respectively). Another variable, PM, indicates the number of months since the previous case of CM and ranges from 0 to 3, where 3 describes greater than or equal to 3 mo since the previous case.

Other parameters included purchase, cull and maintenance costs, monthly involuntary culling risk by lactation for healthy cows, mortality risk at calving and in the postcalving stage, probability of pregnancy (adjusted by being affected with CM, and the effect of CM type on conception), treatment costs and average daily milk loss (kg) since onset of pathogen-specific CM by parity, case, and months elapsed (1, 2, 3+; Bar et al., 2008; Cha et al., 2014). Model parameters, including pathogen incidence, are based on data collected from 23,049 cows over 7 to 8 yr and 50,166 lactations. The cows were from 5 relatively large New York dairy herds using freestall housing, TMR feeding, and parlor milking. Papers relating to data collection and analysis include Schukken et al. (2011, 2013) and Cha et al. (2013). Further details on parameter estimates, model development, and structure can be found in Cha et al. (2014).

The model maximizes net present values for the herd, with possible actions at each month including (1) replacing the cow with a heifer, (2) keeping the cow for another month, without insemination, and treating her if she has CM, and (3) keeping the cow for another month, inseminating her, and treating her if she has CM. The objective function maximized by the model was the discounting criterion; the net present value of the cow was maximized using a yearly interest rate of 8% (Kristensen, 2003; Bar et al., 2008).

Modeling Treatment Scenarios

In modeling our treatment scenarios using the dynamic program, we used a pathogen-specific approach; that is, cows with CM were classified in 9 groups according to the pathogen causing CM. This allowed us to (a) account for a cow's response to treatment (i.e., we assumed that a farmer would not continue to treat a cow that had received effective treatment) and (b) model secondary treatment decisions for cows that did not receive recommended treatment. Secondary treatments refer to follow up treatments given after the initial treatment was not successful. A limitation of this approach is that our model makes decisions (i.e., keep, inseminate, or replace) incorporating the effect of the pathogen causing CM on probability of recurrence, conception, and mortality risk.

Treatment Costs

Treatment costs included the cost of culturing samples to obtain pathogen-specific identification, and the cost of veterinary care, including antibiotic and systemic treatment for a proportion of cases.

Systemic illness was expected in 10% of clinical cases, with the exception of *Staphylococcus* spp. and *Staph. aureus*, and in 20% of *E. coli* and *Klebsiella* cases. The proportion of treated cases, cost, and assumed effectiveness of systemic care was kept constant across treatment protocols, as the same therapy is given for systemic illness due to CM regardless of the causative pathogen. Treatments for each pathogen group were based on published studies of treatment efficacy (Lago et al., 2011; Schukken et al., 2011, 2013; Barlow et al., 2013); costs are described below in US dollars. Costs of drugs were identified by researching online drug sales companies as per Cha et al. (2014); labor was estimated at \$1 per treatment application. Cost of culture was calculated at \$10 per sample, with 24 h of discarded milk while waiting for return of culture results.

Cost, duration, and days of discarded milk for recommended therapies by pathogen group are shown in Table 1. Systemic treatment comprised antibiotics, anti-inflammatories, and fluid therapy with ceftiofur, (Naxcel, Zoetis, Florham Park, NJ), intravenous fluids, and labor for a total of \$13.35 per 10% of cows.

The *Staphylococcus* spp. treatment consisted of antibiotics for 50% of cases, with the recommended treatment cephapirin (Today, Boehringer Ingelheim, St. Joseph, MO) for 1 d and labor for a total cost of \$4.50. Milk discarded due to treatment consisted of 24-h duration of Today treatment + 96-h withdrawal period following final treatment = 5 d, for 50% of cows (2.5 d).

Table 1. Cost and duration of recommended therapies by pathogen group

Treatment protocol 1A	Intramammary treatment	Cost of culture (\$US)	Treatment cost (\$US)	Proportion of cases receiving systemic care (%)	Cost of systemic care for a proportion of cows ¹ (\$US)	Days of discarded milk due to treatment	Total treatment cost (\$US)
<i>Staphylococcus</i> spp.	Cephapirin ² × 1 d for 50% of cows	10	4.50 ³	0	0	2.5	4.50
<i>Staphylococcus aureus</i>	Pirlimycin ⁴ × 8 d	10	44 ⁵	0	0	9.5	44
<i>Streptococcus</i> spp.	Cephapirin × 1 d	10	7 ⁶	10	13.35	5	20.35
<i>Escherichia coli</i>	Ceftiofur ⁷ × 5 d	10	27.50 ⁸	20	26.70	8	54.2
<i>Klebsiella</i>	Ceftiofur × 5 d	10	27.50 ⁸	20	26.70	8	54.2
Other treated	Ceftiofur × 3 d	10	16.50 ⁹	10	13.35	6	29.85
Other not treated	None	10	0	10	13.35	0.15	13.35
Negative culture	None	10	0	10	13.35	0.15	13.35

¹Cost of systemic treatment per 10% of cases: ceftiofur (\$5.00 × 2 doses = \$10), flunixin (\$3 × 2 treatments = \$6), fluids intravenously per os (2.5L × \$7/L = \$17.50) for a total of (\$10 + 6 + \$17.50) × 10% of cows + labor (\$10) = \$13.35.

²Today, Boehringer Ingelheim, St. Joseph, MO.

³Two tubes of treatment in a 12-h period (\$2.50 × 2 = \$5) for 50% of cows and labor (\$2) for a total of \$5.00 × 50% of cows + \$2 = \$4.50.

⁴Pirsue, Zoetis, Florham Park, NJ.

⁵Eight tubes of treatment over 8 d (\$4.50 × 8 = \$36) and labor (\$8) to give \$36 + \$8 = \$44.

⁶Today, 2 tubes of treatment in a 12-h period (\$2.50 × 2 = \$5) and labor (\$2) for a total of \$5 + \$2 = \$7.

⁷Spectramast LC, Zoetis.

⁸Five tubes of treatment over 5 d (\$4.50 × 5 = \$22.50) and labor (\$5) for a total of \$22.50 + \$5 = \$27.50.

⁹Three tubes of treatment over 3 d (\$4.50 × 3 = \$13.50), and labor (\$3) for a total of \$13.50 + \$3 = \$16.50.

Treatment for *Staph. aureus* consisted of pirlimycin (Pirsue, Zoetis) for 8 d and labor for a total cost of \$44. Milk discarded due to treatment consisted of 8 d of treatment + 36-h withdrawal period following final treatment = 9.5 d.

Treatment for *Streptococcus* spp. consisted of cephalapirin (Today, Boehringer Ingelheim) for 1 d, labor and systemic treatment (antibiotics, anti-inflammatory drugs, fluids; see cost of systemic treatment) for 10% of cases (\$13.35) for a total cost of \$20.35. Milk discarded due to treatment consisted of 24-h duration of Today treatment + 96-h withdrawal period following final treatment = 5 d.

Treatment for *E. coli* and *Klebsiella* consisted of ceftiofur (Spectramast, LC, Zoetis) for 5 d, systemic treatment (antibiotics, anti-inflammatory drugs, fluids; see cost of systemic treatment) for 20% of cases, and labor for a total cost of \$54.20. Milk discarded due to treatment consisted of 5-d duration of Spectramast treatment + 72-h withdrawal period following final treatment = 8 d.

Treatment for other treated CM consisted of ceftiofur (Spectramast, Zoetis) for 3 d, labor, and systemic treatment (antibiotics, anti-inflammatory drugs, fluids; see cost of systemic treatment) for 10% of cases (\$13.35) for a total cost of \$29.85. Milk discarded due to treatment consisted of 3-d duration of Spectramast treatment + 72-h withdrawal period following final treatment = 6 d.

Treatment for other not treated CM consisted of systemic treatment for 10% of cows (antibiotics, anti-inflammatory drugs, fluids; see cost of systemic treatment) = \$13.35. Milk discarded due to treatment consisted of 10% of cows × 36 h = 0.15 d.

Treatment for negative culture cases comprised systemic treatment for 10% of cows (antibiotics, anti-inflammatory drugs, fluids; see cost of systemic treatment) = \$13.35. Milk discarded due to treatment consisted of 10% of cows × 36 h = 0.15 d.

Treatment Protocols for Clinical Mastitis

On many farms it is common practice to treat cows without identifying the pathogen causing the mastitis. In this situation, cows may receive treatment that is not recommended or effective for that pathogen. Treatment protocols were developed in consultation with extension veterinarians to reflect common industry practices. Nonrecommended treatments were assumed to be ineffective. Secondary decisions following ineffective treatment included (a) extending the current treatment, (b) alternative treatment, (c) discontinuing treatment, or (d) pathogen identification followed by recommended treatment. The latter option is unlikely

to be adopted on farm, but has been included to allow comparison of the costs of early and late pathogen identification. The alternate treatments selected for (b) are intended to represent drug classes of similar price that function against a similar spectrum of microorganisms. Treatment duration and extensions followed label recommendations. Further treatment beyond the secondary options outlined above was considered unrealistic; therapy was discontinued after this point regardless of predicted cure. Costs of nonrecommended treatments were accounted for as increased treatment costs, and increased milk discarded due to treatment. Treatment protocols are described below.

Scenario 1: Pathogen-Specific Identification Followed by Recommended Therapy. A milk sample from the infected cow is sent for on-farm culture or to an external laboratory to identify the causative pathogen. After 24 h, preliminary culture results are received and the cow is treated with the recommended therapy for that pathogen. Description and cost of recommended therapies for each pathogen group are outlined under treatment costs, and summarized in Table 1.

Scenario 2: Broad-Spectrum Treatment Without Pathogen Identification. The cow is treated with ceftiofur for 5 d. This is often the recommended treatment for *E. coli*, *Klebsiella*, and “other treated” and assumed to be effective for these pathogens. For the remaining pathogens, secondary actions included (2A) extending the current treatment for up to 3 d, (2B) alternate treatment with pirlimycin for 3 d, (2C) discontinuing treatment, or (2D) pathogen identification followed by recommended treatment. Pirlimycin and ceftiofur are the only treatments approved for extended use in lactating animals.

Scenario 3: Treatment with the Cheapest Treatment Option without Pathogen Identification. The cow is treated with cephalixin for 1 d. This is the recommended treatment for *Streptococcus* spp. and *Staphylococcus* spp., and assumed to be effective for these pathogens. For the remaining pathogens, secondary actions included (3A) alternate treatment with Food and Drug Administration-approved treatment such as amoxicillin (Amoxi-Mast, Schering-Plough, Union, NJ) for 3 d ($\$2.60 \times 3 = \7.80), and labor (\$3), for a total cost of \$10.80, (3B) discontinuing treatment, or (3C) pathogen-specific identification followed by recommended treatment.

Effects of Vaccination

The cost of vaccination with a 2-dose J5 bacterin (J-Vac, Merial, Duluth, GA) was \$4.00 ($2 \times \$1.75 = \3.50 ; labor, $2 \times \$0.25 = \0.50). Vaccination was simulated in the model to occur at dry off, and 3 wk before

calving as per label instructions. Effects of vaccination were accounted for as changes in model parameters. Monthly mortality risk was reduced by 0.5 percentage points for cases of coliform CM following vaccination (this was estimated based on Wilson et al., 2007). Daily milk loss due to mastitis was reduced by 7.6 kg/d for 21 d following coliform CM (Wilson et al., 2008). To account for this within the time frame of the model, we reduced milk loss in mo 0 (first 3 d of lactation) by 7.6 kg, and milk loss in mo 1 (the following 27.5 d of lactation) by an adjusted value ($7.6 \text{ kg} \times 21 \text{ d of effectiveness} - 3 \text{ d of mo 0 already accounted for} / 27.5 \text{ d of lactation in mo 1} = 4.97 \text{ kg of milk loss per day of mo 1}$). Incidence of *E. coli* CM with vaccination was reduced by 80% (Gonzalez et al., 1989), 70% (Cullor, 1991), and not at all (Wilson et al., 2007) in mo 0, 1, and 2 in the model. This allows 61 d of vaccination effectiveness, which is slightly more than the 50 d of vaccine effectiveness reported by Wilson et al. (2009), but is the closest input value possible within the time step of the model.

We simulate the effects of the whole herd being vaccinated and compare that with the same herd that is not vaccinated (i.e., without these effects). This involves changes to parameter estimates at the individual cow level, which we simulate to extrapolate to the herd level. Reduced severity of cases of coliform CM in vaccinated cows was indirectly accounted for by modeling reduced milk loss in cases of coliform CM. We assume in our model that farmers who vaccinate their cows will continue to vaccinate their cows, and that the effects of vaccination will last for the duration of the cows' use.

Effects of Different Treatment Protocols and Vaccination

The average net returns/cow per year following each treatment protocol were estimated using the model and compared. The model optimizes replacement decisions, which may reduce the cost of CM compared with its actual cost on farms. However, this applies to all scenarios, allowing their economic comparison relative to each other. The percentage of cows receiving recommended treatment was calculated for each treatment protocol using the pathogen incidences detailed in Table 1, and the treatment spectrum of each drug as per label indications.

Average cost of CM by pathogen group and treatment protocol was estimated by subtracting the average net returns/cow per year in a herd with CM from the average net returns/cow per year in a herd without CM caused by each pathogen group while keeping other parameters constant. Cost of CM for each treatment protocol incorporated reduced milk production due to

Table 2. Average net returns and percentage of cows receiving recommended treatment by treatment protocol

Treatment protocol	Average net returns ¹ (\$US)	% of cows receiving recommended treatment ²
1 ³	505	100
2A ⁴	488	71
2B ⁵	489	100
2C ⁶	495	71
2D ⁷	490	100
3A ⁸	507	68
3B ⁹	510	68
3C ¹⁰	500	100

¹Average net returns per cow per year in US dollars.²Percentage of cows receiving recommended treatment per all clinical mastitis (CM) cases.³Pathogen-specific identification followed by recommended treatment.⁴Broad-spectrum treatment without pathogen identification, where secondary action is to extend the current treatment for 3 d.⁵Broad-spectrum treatment without pathogen identification, where secondary action is alternate treatment with pirlimycin for 3 d.⁶Broad-spectrum treatment without pathogen identification, where secondary action is to discontinue treatment.⁷Broad-spectrum treatment without pathogen identification, where secondary action is pathogen-specific identification followed by recommended treatment.⁸Treatment with the cheapest treatment option without pathogen identification, where secondary action is alternate treatment with amoxicillin.⁹Treatment with the cheapest treatment option without pathogen identification, where secondary action is to discontinue treatment.¹⁰Treatment with the cheapest treatment option without pathogen identification, where secondary action is pathogen-specific identification followed by recommended treatment.

CM, treatment costs, discarded milk due to treatment, reduced conception, and increased risk of mortality. The cost of CM for each pathogen group was then divided by the herd incidence of that pathogen to give the average cost per case by treatment protocol for each pathogen group.

The cost-benefit of vaccination was evaluated by comparing the average net returns/cow per year under scenario 1 (pathogen-specific identification followed by recommended therapy), with the average net returns/cow per year of vaccinated animals under scenario 1 where incidence of coliform CM was reduced by 80%, 70%, and 0, in combination with changes to milk loss and mortality. Scenario 1 was chosen as the base scenario as it is recommended practice, and involves 100% of infected cows receiving recommended treatment in the primary instance of infection.

RESULTS

The average net returns and proportion of cows receiving recommended treatment for each treatment protocol are presented in Table 2. Treating cows without pathogen identification using the cheapest treatment option, and discontinuing treatment where this was not effective, yielded the highest net returns. This was simply because treatment costs were reduced through not providing treatment, and these treatment protocols resulted in the lowest proportion of infected cows receiving recommended treatment. Of the treatment scenarios where 100% of cows received recommended treatment, pathogen-specific identification followed by recommended therapy yielded the highest net returns.

The results of vaccination are presented in Table 3. Vaccination increased average net returns in all scenarios regardless of whether it reduced incidence. Vaccination increased the proportion of *E. coli* cases treated, and had no effect on mortality and culling overall.

The average cost per case of CM by pathogen group and treatment protocol is presented in Table 4. Incidence of CM totaled 35.6 cases per 100 cow years. These consisted of *Staphylococcus* spp. (1.6), *Staph. aureus* (1.8), *Streptococcus* spp. (6.9), *E. coli* (8.1), *Klebsiella* spp.

Table 3. Effects of J5 vaccination following reduction in incidence of coliform mastitis (CM) by 80%, 70%, and 0

Vaccination status	Average net returns ¹ (\$US)	Involuntary culling ² (%)	Voluntary culling ³ (%)	Incidence of <i>E. coli</i> CM ⁴ (%)	% of <i>E. coli</i> cases treated ⁵ (%)
No vaccination	505	10.31	20.21	8.1	86.6
Vaccination 1 ⁶	510	10.31	20.12	8.1	90.6
Vaccination 2 ⁷	513	10.17	20.22	7.3	89.6
Vaccination 3 ⁸	513	10.16	20.23	7.2	89.5

¹Average net returns per cow per year in US dollars.²Annual exit from the herd (%) due to causes unrelated to treatment decisions.³Annual exit from the herd (%) due to culling recommended by the model.⁴Incidence of CM caused by *Escherichia coli* per 100 cow years.⁵Percentage of *E. coli* CM cases recommended to receive treatment.⁶Vaccination where incidence of coliform CM is not reduced.⁷Vaccination where incidence of coliform CM is reduced by 70%.⁸Vaccination where incidence of coliform CM is reduced by 80%.

(2.2), other treated cases (1.1), other not treated cases (1.2), and negative culture cases (12.7). For scenario 1, the average cost per case was greatest for *Klebsiella* spp. (\$459), followed by *E. coli* (\$373) and other not treated (\$281). Other treated was the next most costly (\$275), followed by *Staph. aureus* (\$278), *Streptococcus* spp. (\$175), and *Staphylococcus* spp. (\$151). Negative culture had the lowest cost (\$97). In scenarios where all cows received recommended treatment, pathogen specific identification followed by recommended treatment had the most consistently low average cost per case.

DISCUSSION

We found that vaccination increased average net returns in all scenarios. Net returns increased by \$5, or 1.0%, per cow, with no reduction in incidence, and \$8, or 1.6% per cow where incidence was reduced by 80%. We attribute the increase in net returns without a reduction in incidence to the reduced milk loss of cases of coliform CM in vaccinated cattle. Mortality and culling were not affected by vaccination, although the model recommended a higher proportion of vaccinated cows with *E. coli* CM being treated than unvaccinated cows. The increased number of cows treated, and therefore not culled due to CM, may indirectly account for a reduction in severity of *E. coli* CM in our model. Vaccination has been reported to reduce severity of coliform CM cases and culling due to mastitis (Wilson et al., 2007).

In our model, the effect of vaccination does not differ between lactations. Therefore, the effect (in terms of changes to mortality risks, milk loss, and incidence of and due to coliform mastitis) of vaccination is altered for all lactations for all cows within a vaccinated herd. We could examine the performance of individual animals that are vaccinated by including another state; however, this would increase the state space and we could encounter the problem of the curse of dimensionality where the model cannot converge due to the large state space. The structure of this analysis may be improved with more information on the duration of vaccine efficacy, but would likely continue to show that vaccination is beneficial.

Future models could account for severity of CM, which may influence treatment decisions and mortality if treatment were to be delayed or ineffective. However, the subjective nature of measuring severity creates issues for reliable data collection across herds. Incorporating a reduction of severity as an effect of vaccination may have had further effects, such as reducing treatment costs, which would make vaccination more cost effective.

Table 4. Average cost per case (ACC) of clinical mastitis (CM) by pathogen group and treatment protocol

Pathogen group	CM incidence ¹	CM cases treated (%) ²	1 Average cost per cow (\$US) ⁴	Treatment protocol ³							
				1 ACC (\$US) ⁵	2A ACC (\$US)	2B ACC (\$US)	2C ACC (\$US)	2D ACC (\$US)	3A ACC (\$US)	3B ACC (\$US)	3C ACC (\$US)
<i>Staphylococcus</i> spp.	1.6	97	2	151	250	239	218	242	154	152	159
<i>Staphylococcus aureus</i>	1.8	88.1	5	278	286	275	254	339	208	194	286
<i>Streptococcus</i> spp.	6.9	92.5	12	175	244	233	205	238	160	157	164
<i>Escherichia coli</i>	8.1	86.6	30	373	369	369	364	367	330	319	384
<i>Klebsiella</i>	2.2	83.6	10	459	455	455	452	455	422	413	469
Other treated	1.1	93.4	2	275	310	310	283	296	266	247	287
Other not treated	1.2	91.2	3	281	368	370	342	355	312	302	316
Negative culture	12.7	94.3	12	97	173	173	152	161	130	119	127

¹CM cases per 100 cow years.

²Percentage of CM cows receiving treatment per all CM cows.

³Treatment protocols described in Table 2.

⁴Average net returns per cow per year in a herd without CM minus average net returns per cow per year in a herd with CM.

⁵Average cost per cow divided by number of CM cases.

Some of the treatment scenarios ended in discontinued treatment and no recommended treatment being given to particular pathogen groups. This reduced losses due to treatment costs and discarded milk, causing them to appear most cost effective. Spontaneous cure is a possible outcome for cows that are not treated; however, this is difficult to define and often different for each pathogen. The time to meet the cured definition (e.g., milk appearance, SCC change, or both) can vary from days to months. Although the cow is likely to recover without treatment given time, recovery may take longer than it would had the cow received appropriate treatment. This could result in reduced milk yield and the production of poorer quality, high SCC milk for a longer period following CM, and an associated loss of income. Therefore, the relatively lower cost of treatment protocols where a low percentage of cows received recommended treatment may not accurately reflect their actual cost had these effects been incorporated.

In our study, we assumed that recommended treatment is 100% effective and that the farmer would not extend or alternate treatment if he had used this treatment initially. In the real world, individual cows may respond differently to treatment, and farms may have predominant pathogen strains that differ in their susceptibility to medications. Additionally, not all treatments are effective against pathogens causing CM. Pathogen identification allows farmers to more easily identify cows that may respond to treatment, and to not treat or cull cows with a low probability of cure, thereby reducing inappropriate use of antibiotics. Farmers may elect not to treat cows based on severity, cow history, likelihood of cure, and other factors. Our model accounts for this by incorporating cow characteristics such as CM history, genetic potential, milk yield, and conception rates to generate the net present value of the cow against which treatment decisions are made. Although the treatment decisions modeled are economic optimizations and cannot capture the potential decisions of individual farmers to treat or not treat their cows, this is consistent between scenarios, allowing their comparison relative to each other.

Culling and insemination decisions are also influenced by pathogen-specific effects on risk of recurrence, conception, and mortality. However, a farmer's treatment decisions cannot be influenced by the type of pathogen causing CM if he does not know which pathogen is causing CM (i.e., in a treatment scenario without pathogen identification). By accounting for these factors, we are assuming the farmer has more information than he actually has. Within our model structure, it is not possible to model the treatment scenarios in a way that accounts for response to treatment and secondary treatment decisions without incorporating these

other pathogen-specific effects. The alternative option is to use a generic approach, where all cases of CM are treated as if they were caused by one pathogen group. Although this keeps pathogen effects on treatment decisions constant, by assuming a blanket treatment approach it does not allow us to account for response to treatment, secondary treatment decisions for different cows, and is less realistic in that a farmer is unlikely to treat all cows with CM as if it were caused by only one pathogen. We therefore used a pathogen-specific approach to model treatment scenarios as it allowed us to model more realistic treatment situations. Additionally, the pathogen-specific effects on recurrence, conception, and mortality are consistent throughout all treatment scenarios, and our results are intended as relative comparisons and not as absolute figures.

Few published data exist quantifying the effects of giving therapy other than the recommended therapy for cows with CM, and we were limited by this to modeling cost in terms of treatment cost and days of discarded milk. Had more data on the effects of mismatched treatment on cure rates, conception, milk loss and mortality been available and accounted for in the model, it would likely cause pathogen-specific therapies to be more cost effective relative to other treatment protocols. In our model, we assumed that drugs had no efficacy for pathogen groups for which they were not recommended. The lack of studies quantifying partial efficacies of different treatments against different pathogens prevented this inclusion in our model. If data on treatment effects were available, these parameters would afford more realistic economic comparisons between treatment protocols.

Further, the treatment scenarios explored involved switching treatment at 5 d (i.e., within the 1 mo time step in the model). This simplifies the treatment effects such that they would all occur within the 1 mo. Segregating the months into smaller units, though more accurate, would have enlarged the state space of the model to be greater than can be handled by the average personal computer. The lack of data on treatment effects led the input values to be directed by treatment cost and days of discarded milk.

Developing a model based on bulk milk tank parameters could be one way to incorporate relevant effects of treatment decisions on milk production and milk quality, without being limited by the availability of published data on these specific effects. That is, the milk yield and SCC production of all cows contributes to the volume and value of milk sold. Developing a model that makes decisions based on the combined yield and SCC of all the cows in the herd could help to identify an optimal combination of cows to have. For example, if it would be better to have high-producing, high-SCC

cows or lower-producing, low-SCC cows in the herd or a combination thereof. Shifting the decision-making focus in the model from individual cow to whole herd management would allow the incorporation of broader effects of clinical and subclinical mastitis, such as the production of high SCC milk devaluing the overall price of milk for the herd, and may better reflect economic priorities on farm.

The model optimizes decisions to keep, inseminate, and cull cows, and the absolute values for each policy may not reflect actual, on-farm figures. It also assumes that a correct diagnosis cannot be made based on clinical signs and a farmer's experience. Modeling treatment protocols as an inflexible set of decisions may not reflect exactly what happens on individual farms for the above reasons, but does enable effects (e.g., milk loss) to be incorporated beyond what a farmer could calculate in a direct appraisal of an individual case. This allows for a detailed economic comparison of different treatment protocols to be made, providing a guide for farmers to develop economically optimal treatment protocols.

CONCLUSIONS

Pathogen-specific identification followed by recommended treatment, in combination with J5 vaccination, is economically optimal relative to other treatment protocols where all cows received recommended treatment. Out of all treatment scenarios, the highest net returns were achieved with selecting the cheapest treatment option and discontinuing treatment, or switching to a similar spectrum therapy. However, this apparent cost effectiveness only reflects reduction of loss from treatment costs and discarded milk, and only two-thirds of cows received recommended treatment in these scenarios. Were it possible to account for the full consequences of giving nonrecommended therapies to cows with CM, pathogen-specific identification followed by recommended therapy would likely be more cost effective relative to this approach. J5 vaccination increased net returns in all scenarios.

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